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Cleveland, OH

SOFTWARE TOOLS TO SUPPORT THE ASSESSMENT OF SYSTEM HEALTH

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This presentation provides an overview of three software tools that were developed by the NASA Glenn Research Center to support the assessment of system health: the Propulsion Diagnostic Method Evaluation Strategy (ProDiMES), the Systematic Sensor Selection Strategy (S4), and the Extended Testability Analysis (ETA) tool. Originally developed to support specific NASA projects in aeronautics and space, these software tools are currently available to U.S. citizens through the NASA Glenn Software Catalog.

The ProDiMES software tool was developed to support a uniform comparison of propulsion gas path diagnostic methods. Methods published in the open literature are typically applied to dissimilar platforms with different levels of complexity. They often address different diagnostic problems and use inconsistent metrics for evaluating performance. As a result, it is difficult to perform a one-to-one comparison of the various diagnostic methods. ProDiMES solves this problem by serving as a theme problem to aid in propulsion gas path diagnostic technology development and evaluation. The overall goal is to provide a tool that will serve as an industry standard, and will truly facilitate the development and evaluation of significant Engine Health Management (EHM) capabilities. ProDiMES has been developed under a collaborative project of The Technical Cooperation Program (TTCP) based on feedback provided by individuals within the aircraft engine health management community.

The S4 software tool provides a framework that supports the optimal selection of sensors for health management assessments. S4 is structured to accommodate user-defined applications, diagnostic systems, search techniques, and system requirements/constraints. One or more sensor suites that maximize this performance while meeting other user-defined system requirements that are presumed to exist. S4 provides a systematic approach for evaluating combinations of sensors to determine the set or sets of sensors that optimally meet the performance goals and the constraints. It identifies optimal sensor suite solutions by utilizing a merit (i.e., cost) function with one of several available optimization approaches. As part of its analysis, S4 can expose fault conditions that are difficult to diagnose due to an incomplete diagnostic philosophy and/or a lack of sensors. S4 was originally developed and applied to liquid rocket engines. It was subsequently used to study the optimized selection of sensors for a simulation-based aircraft engine diagnostic system.

The ETA Tool is a software-based analysis tool that augments the testability analysis and reporting capabilities of a commercial-off-the-shelf (COTS) package. An initial diagnostic assessment is performed by the COTS software using a user-developed, qualitative, directed-graph model of the system being analyzed. The ETA Tool accesses system design information captured within the model and the associated testability analysis output to create a series of six reports for various system engineering needs. These reports are highlighted in the presentation. The ETA Tool was developed by NASA to support the verification of fault management requirements early in the Launch Vehicle process. Due to their early development during the design process, the TEAMS-based diagnostic model and the ETA Tool were able to positively influence the system design by highlighting gaps in failure detection, fault isolation, and failure recovery.



SOFTWARE TOOLS TO SUPPORT THE ASSESSMENT OF SYSTEM HEALTH

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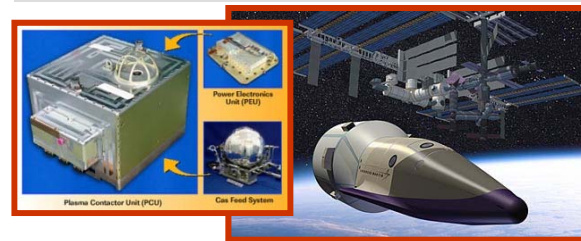
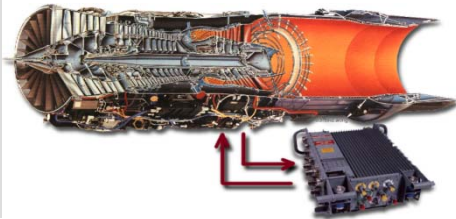


Outline

- ❑ **Background**
- ❑ **Software Tools**
 - ❑ **Propulsion Diagnostic Method Evaluation Strategy (ProDIMES)**
 - ❑ **Systematic Sensor Selection Strategy (S4)**
 - ❑ **Extended Testability Analysis (ETA) Tool**
- ❑ **Concluding Remarks**
- ❑ **References**



NASA Glenn Controls & Dynamics Branch



Active Clearance Control

- Clearance Modeling
- Mechanical/Smart Materials Actuation Requirements

Active Flow Control

- High Bandwidth Actuation
- Stall Control
- Smart Vanes
- Turbine Film Cooling Control

Active Combustion Control

- Emission Minimization
- Control of Thermo-acoustic Instability

Advanced Control Logic

- Intelligent Adaptive Control
- Life Extending Control
- Resilient Propulsion Control

System Health Management for Propulsion, Power, & Ground Systems

- Sensor Selection & Validation
- Fault Diagnosis & Classification
- Prognostics
- Post Test Diagnostic Systems
- Communication Requirements
- Real-Time Implementation Issues

Current NASA Programs

Aeronautics Research Mission

- Fundamental Aeronautics
- Aviation Safety

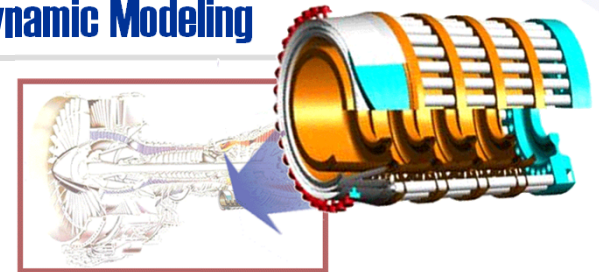
Exploration Systems Mission

- Space Launch System
- Ground Systems Development and Operations

Maintainability & Reliability

- Autonomous Mobile Robotic Inspection & Repair

Dynamic Modeling

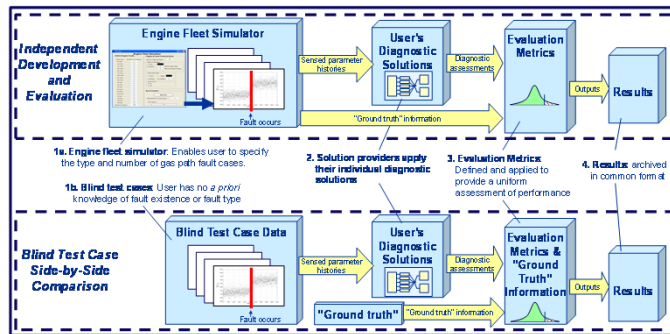


Advanced Propulsion Concepts

- Pulse Detonation Engine
- Fuel Cell Powered Aircraft
- Wave Rotors
- High-speed Systems

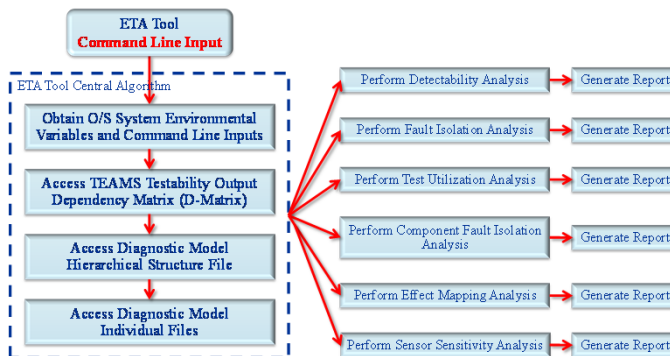
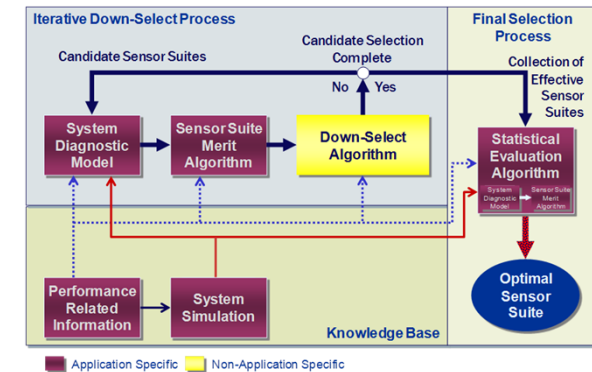


NASA Glenn Controls & Dynamics Branch Software Tools for System Health Assessment



ProDIMES: Propulsion Diagnostic Method Evaluation Strategy
Supports fair, quantitative benchmark comparisons of aero engine gas path diagnostic methods.

S4: Systematic Sensor Selection Strategy
Software framework for performing optimal selection of sensors required to support system health assessment



ETA Tool: Extended Testability Analysis Tool

Testability analyses that support qualitative verification of system health requirements early in the design process.



Acknowledgements

ProDIMES Team

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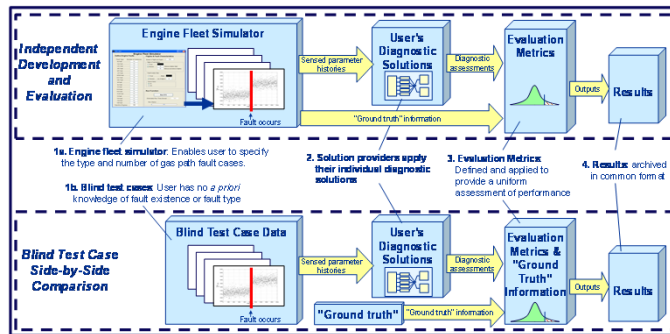
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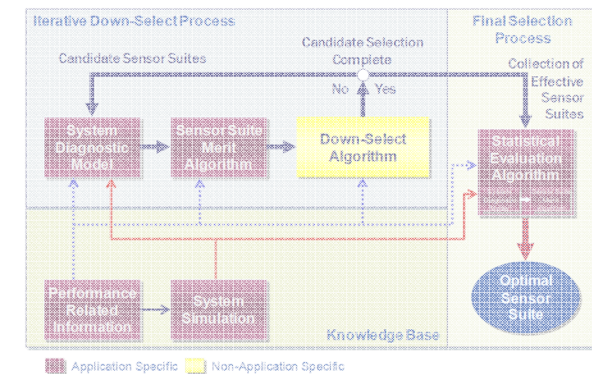


NASA Glenn Controls & Dynamics Branch Software Tools for System Health Assessment

ProDIMES: Propulsion Diagnostic Method Evaluation Strategy



S4: Systematic Sensor Selection Strategy



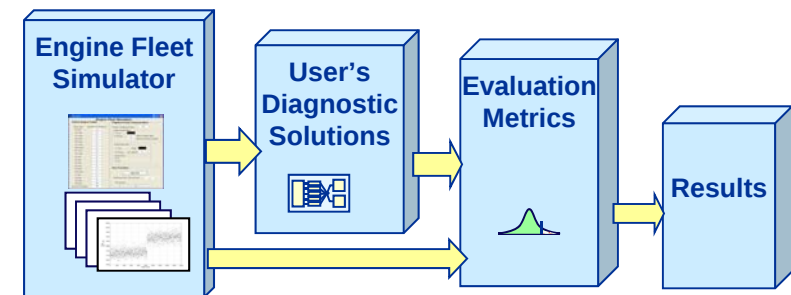
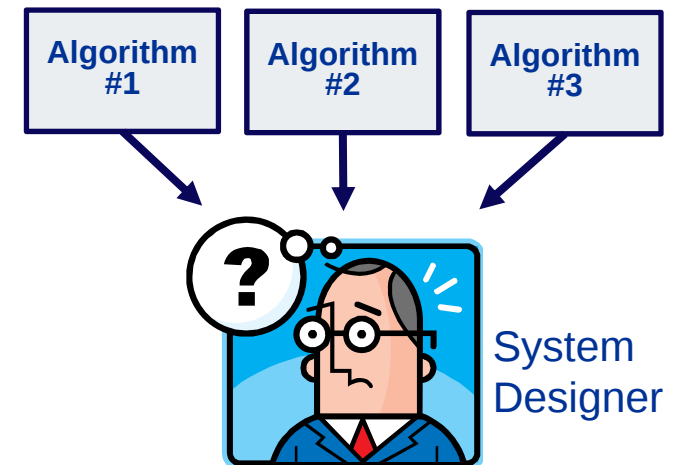
ETA Tool: Extended Testability Analysis Tool



Propulsion Diagnostic Method Evaluation Strategy (ProDiMES)

A Public Approach for Benchmarking Gas Path Diagnostic Methods

- Engine Health Management (EHM) related R&D activities have increased significantly since the late 1990's. However, due to the use of different terminologies, applications, proprietary data, and metrics there is no basis of comparison
- Public benchmarking problems can facilitate the development and comparison of candidate health management methods against a common problem
- ProDiMES provides a simulated aircraft engine gas path diagnostic benchmarking problem
 - Developed as part of a collaborative project under The Technical Cooperation Program (TTCP)
 - Available through the NASA Glenn Software Catalog



ProDiMES Architecture

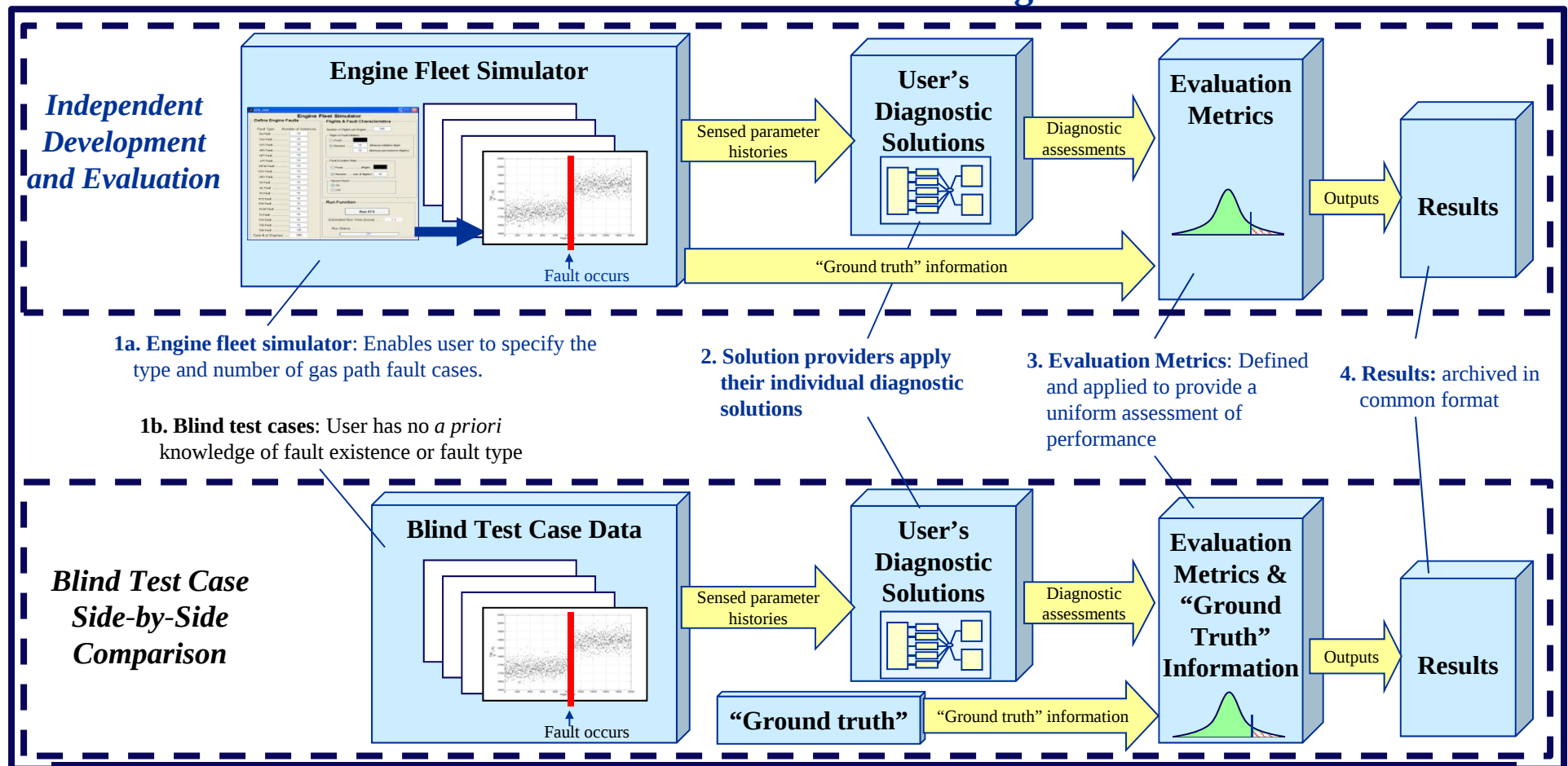


Propulsion Diagnostic Method Evaluation Strategy (ProDiMES)

ProDiMES Diagnostic Benchmarking Process

***ProDiMES enables independent development and evaluation
and a blind test case comparison***

ProDiMES Public Benchmarking Process



1a. Engine fleet simulator: Enables user to specify the type and number of gas path fault cases.

1b. Blind test cases: User has no *a priori* knowledge of fault existence or fault type

2. Solution providers apply their individual diagnostic solutions

3. Evaluation Metrics: Defined and applied to provide a uniform assessment of performance

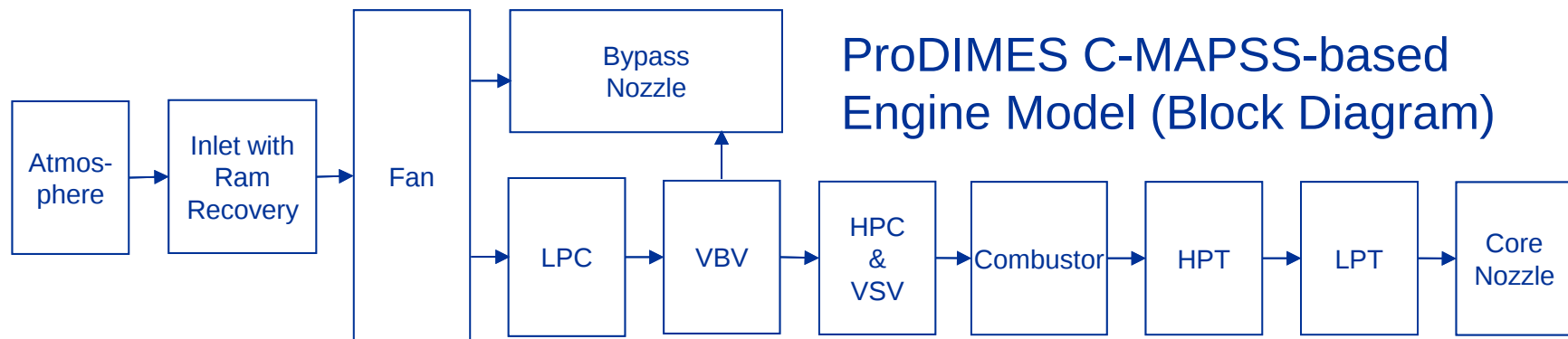
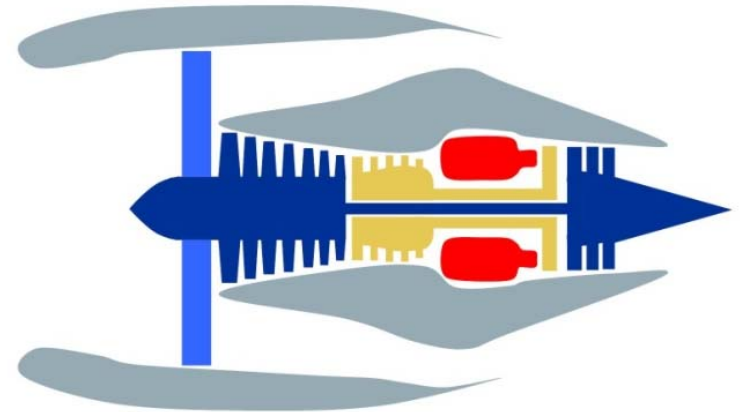
4. Results: archived in common format



Propulsion Diagnostic Method Evaluation Strategy (ProDiMES)

Commercial Modular Aero-Propulsion System Simulation

- Engine model representative of a large commercial turbofan
- NASA-developed, Matlab/Simulink-based, generic, non-linear, component-level model with closed-loop control
- Uses 13 health parameters to model engine performance degradation due to engine wear and faults.
- Generates 11 sensed outputs
 - 3 aircraft parameters (P_{amb} , P_2 , T_2)
 - 8 engine measurements (N_f , N_c , P_{24} , P_{s30} , T_{24} , T_{30} , T_{48} , W_{f36})
- ProDiMES EFS uses core elements of C-MAPSS:
 - Steady-state solver balances engine to specified operating point
 - No closed-loop control logic or transient operating capability
 - Includes logic to ensure that operating limits are not violated
 - Captures coupled fault effects (e.g., a corrected rotor speed sensor fault will result in mis-scheduled variable geometry).

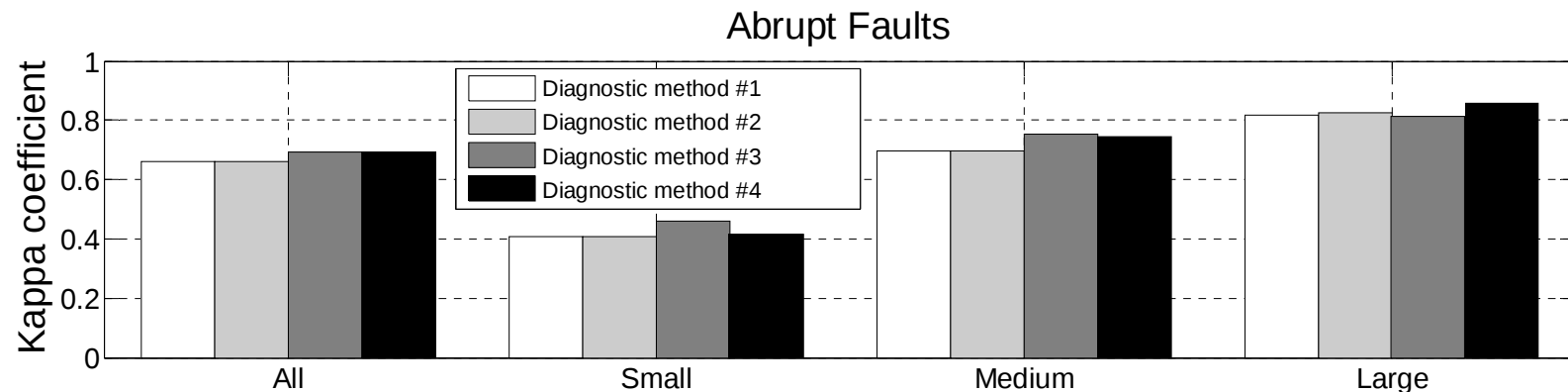




Propulsion Diagnostic Method Evaluation Strategy (ProDiMES)

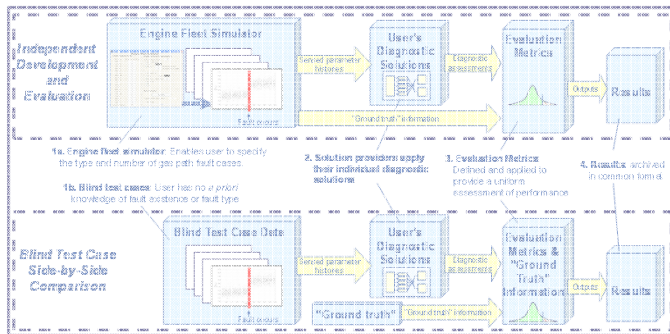
ProDiMES Blind Test Case Comparison Results

- A 2012 workshop was held for ProDiMES users to share diagnostic results and lessons learned.
 - ProDiMES was found to provide a suitably challenging problem.
 - Users welcomed the opportunity to assess and compare diagnostic methods against a standard benchmark problem.
- The results of four diagnostic methods applied to the blind test case data set were assessed and compared (a portion of the metric results are shown below)
 - Follow-on collaborative assessments conducted by ProDiMES participants have shown improved diagnostic performance obtained by pairing the best performing detection and classification approaches.



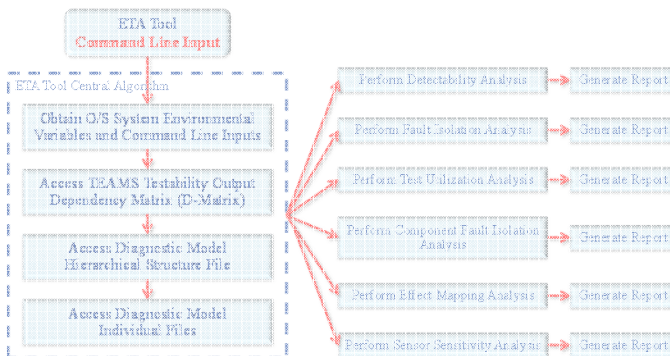
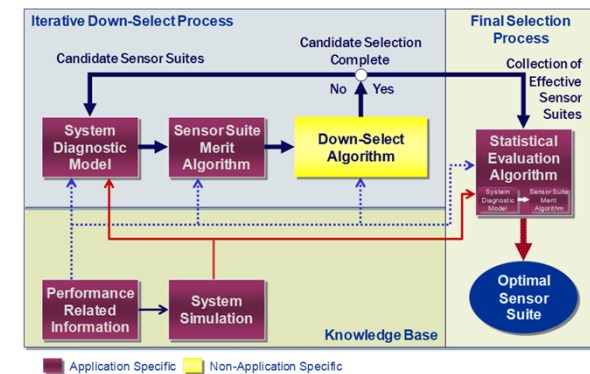


NASA Glenn Controls & Dynamics Branch Software Tools for System Health Assessment



ProDIMES: Propulsion Diagnostic Method Evaluation Strategy

S4: Systematic Sensor Selection Strategy



ETA Tool: Extended Testability Analysis Tool

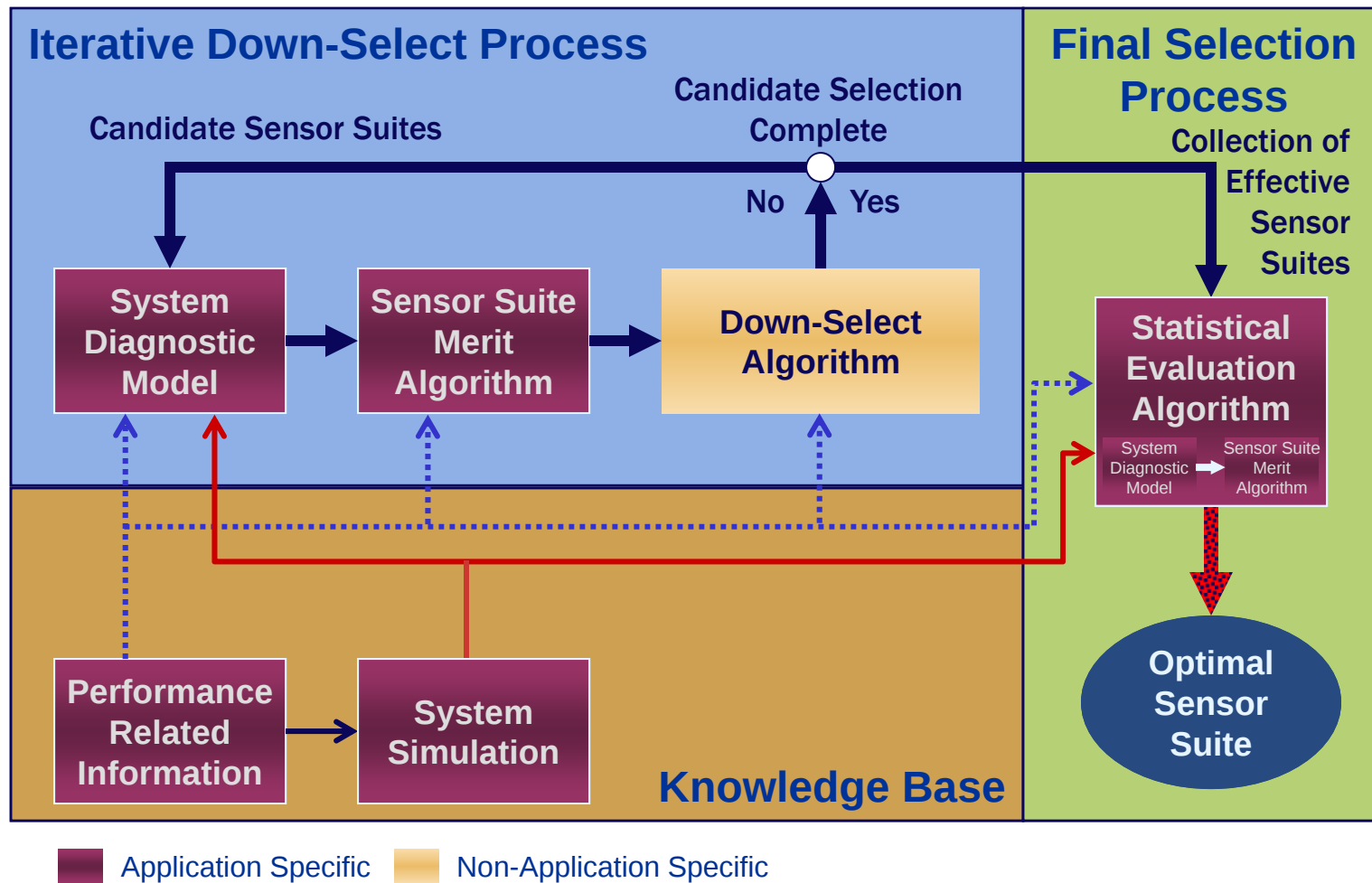


Motivation for Optimizing Sensor Selection

- Traditional aerospace approaches to sensor selection are:
 - Generally qualitative approaches based on engineering judgment and/or heuristics
 - Oriented toward operations, controls and/or performance
 - May not provide coverage required to manage system health
- Systematic Sensor Selection Strategy (S4)
 - Used in simulation-based studies to optimally identify sensors needed to manage the health of liquid rocket engines (MC-1, RS-83, RS-84, X-34) and aircraft turbine engines.
 - Model-based approach identifies a set of sensors that optimally meets application-specific design objectives
 - Single-valued user-defined metric (i.e., cost) function employed to quantitatively assess capability of various sensor combinations to meet multiple design objectives
 - Flexible two-stage optimization approach with broad applicability

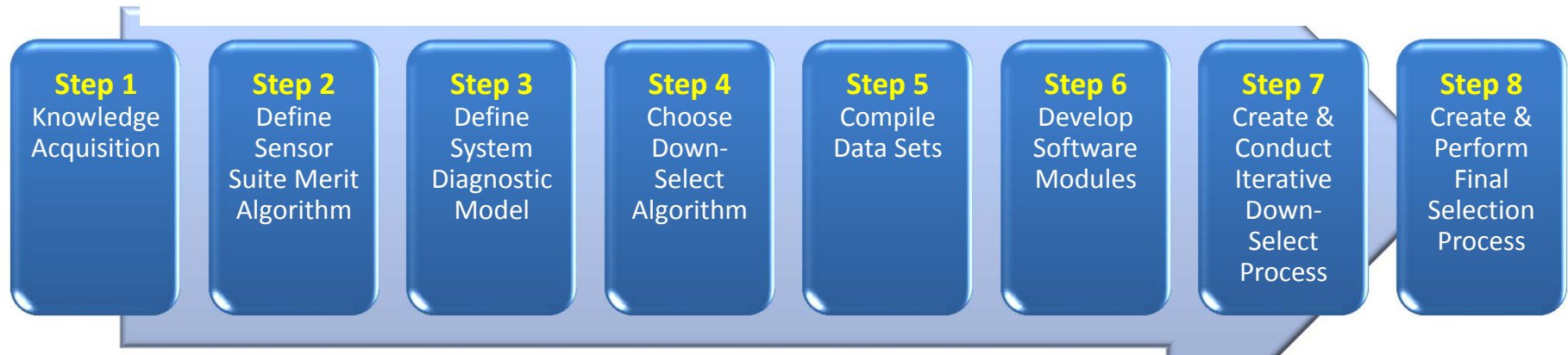


S4 Framework





Generalized S4 Implementation Process



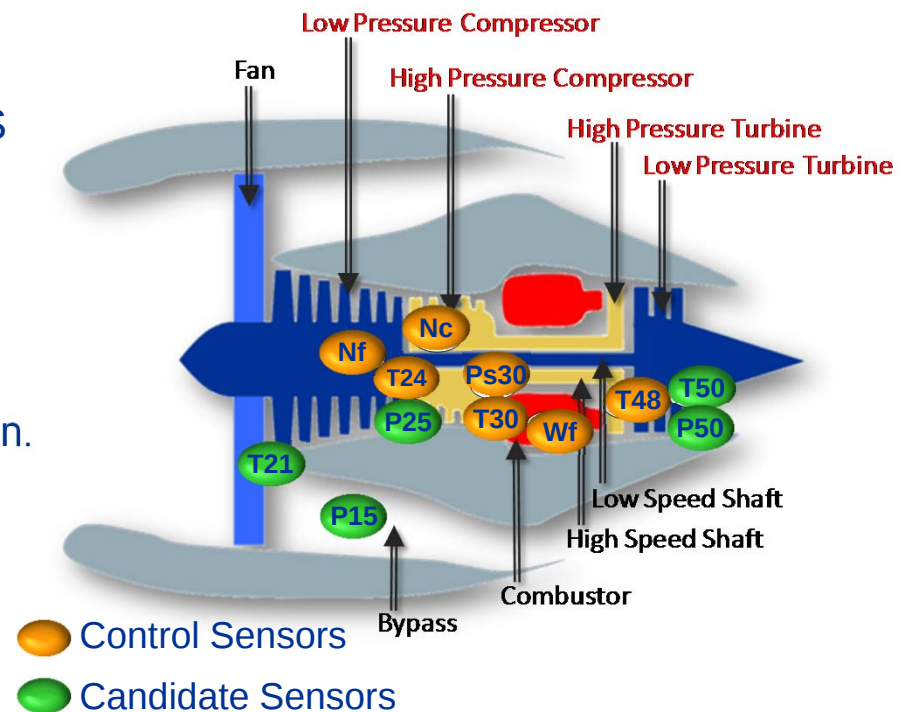
- Eight-step process defined as *guideline* for implementing elements of the S4 framework as part of a user-defined application
- Significant flexibility – early steps can be reordered at user's discretion
- Some iteration likely during implementation of early steps
- Detailed description of implementation process contained in NASA/CR—2012-215242 S4 User Guide (see references)



S4 Use Case Implementation (1/3)

Step 1: Knowledge Acquisition

- Goal: Collect data required to implement user's S4 application
- S4 C-MAPSS Use Case
 - Optimization based on seven (7) control sensors and five (5) candidate sensors
 - Data for four (4) fault cases: fan, high pressure compressor, high pressure turbine, and low pressure turbine.
 - Each fault modeled as simultaneous adjustments to associated C-MAPSS efficiency and flow capacity health parameters.
 - Model reference & test case data
 - Used to assess sensor suite failure detection and fault isolation.
 - Data conditioning improves algorithm stability





S4 Use Case Implementation (2/3)

Step 2: Define Sensor Suite Merit Algorithm

- Goal: Define algorithm that will be used to quantify optimality
- S4 C-MAPSS Use Case

For each sensor suite k

$$M_k = P_k \cdot D_k = \frac{1}{w_k \cdot |N_d - N_k| + 1} \cdot \sum_{j=1}^n C_j Z_{jk}$$

where

- M_k Merit Value – Value of the Merit Algorithm for sensor suite k .
- P_k Penalty Term – Reduces merit value (M_k) as number of sensors in suite k deviates from the preferred number of sensors, $N_d = 9$.
- D_k Diagnostic Performance Score – Provides quantitative assessment of the diagnostic performance of sensor suite k .
- C_j Criticality Factor – Weighting term for fault case j based on fault criticality and/or probability of occurrence. For this use case = 1.
- Z_{jk} Fault Diagnostic Performance Metric – Qualitative assessment of the diagnostic performance of sensor suite k for fault case j .



S4 Use Case Implementation (3/3)

Steps 7 & 8: Create/Perform Iterative Down-Select & Final Selection Processes

- Goal: Develop and execute software code for processes that perform the optimization.

- S4 C-MAPSS Use Case

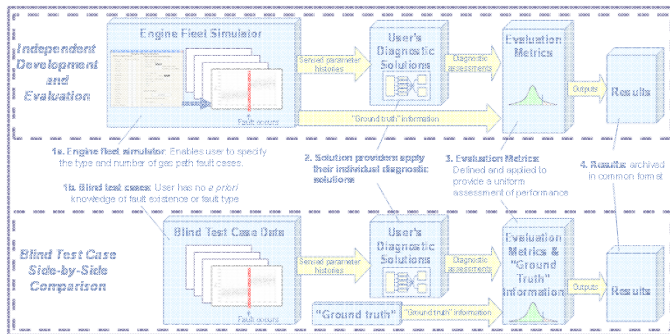
- Iterative Down-Select Process
 - Implemented with Genetic Algorithm
 - After 5 generations, highest performing sensor suites are identified
- Final Selection Process
 - Selected 3 highest performing sensor suites for more rigorous evaluation
 - Confirms results of Iterative Down-Select Process

	Sensor Suite Merit Value	
Add'l Candidate Sensors	Iterative Down-Select Process	Final Selection Process
T50, P50	23.0418	22.4238
P25, T50	22.0360	20.8636
P25, P50	22.0360	20.8636



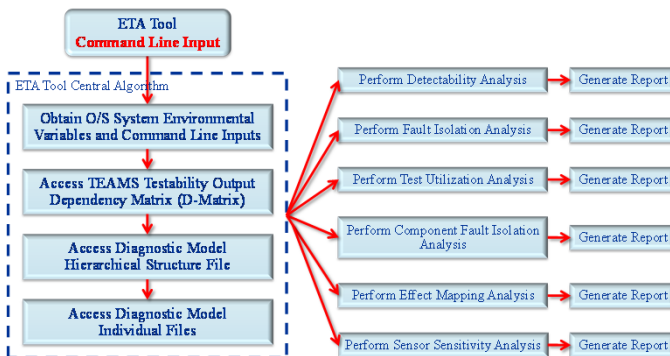
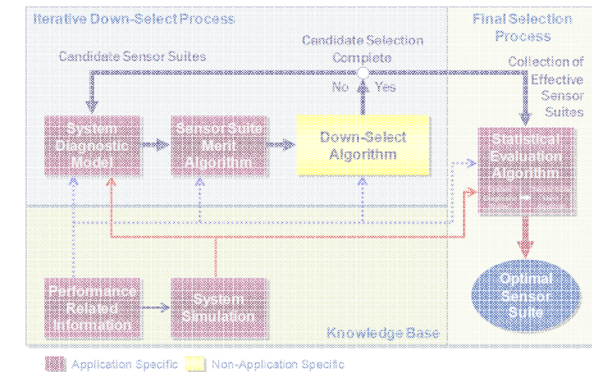
NASA Glenn Controls & Dynamics Branch

Software Tools for System Health Assessment



ProDIMES: Propulsion Diagnostic Method Evaluation Strategy

S4: Systematic Sensor Selection Strategy



ETA Tool: Extended Testability Analysis Tool



Model-based Testability Analysis

Model-based Testability Analysis

- Qualitative diagnostic approach based on a fault propagation model of the system
- Generates Dependency Matrix that relates failure modes to failure detection tests

Approach

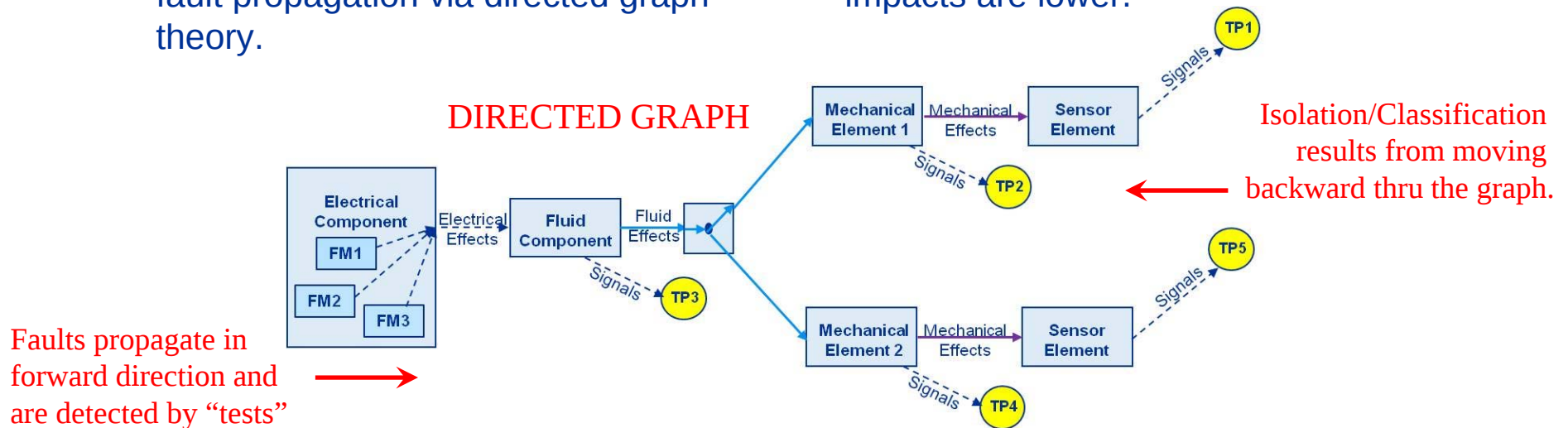
- TEAMS Designer (commercial-off-the-shelf software) used to model fault propagation via directed graph theory.

Motivation

- Multiple system-level goals for Safety, Reliability, Maintainability and Availability lead to various diagnostic-related requirements levied against the system or subsystem.

Benefits

- Model-based verification of diagnostic requirements early in the design process enables redesign when cost impacts are lower.



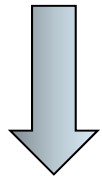


ETA Tool Overview

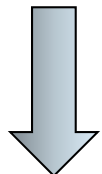
Qualitative Functional Fault Model with Testability Analysis

Schematic

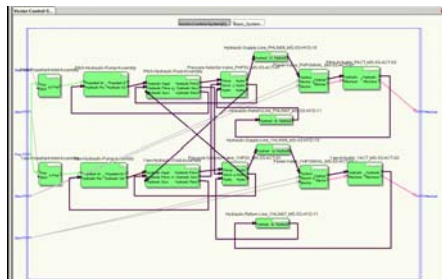
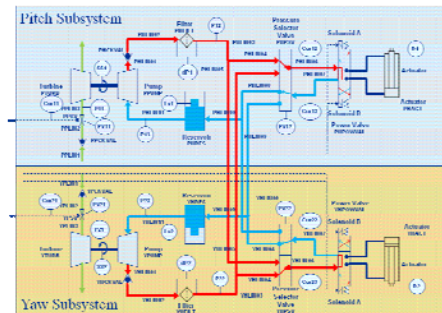
+
FMEA



COTS
Modeling
Software



Dependency
Matrix
(D-Matrix)



Failure Mode Tests				
Failure Modes	1	0	1	0
	0	1	1	1
	1	1	1	0
	1	0	1	1

Extended Testability Analysis (ETA) Tool

Gov't Dev. Effort

- Stand-alone software tool developed to support Ares Program
- Provides additional analyses and detailed reporting capabilities

Commercialization Effort

Government/Industry partnership integrated ETA tool modeling conventions, analyses, and reports into existing COTS software package to support future NASA programs.

Failure Detectability

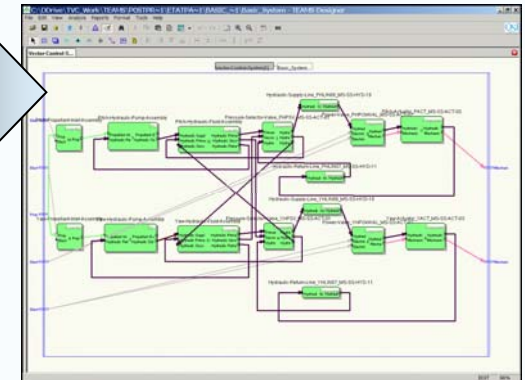
Test Utilization

Failure Isolation

Component Failure Isolation

Effect Mapping

Sensor Sensitivity



Stand-alone software available from the NASA Glenn Software Catalog at:
<https://sr.grc.nasa.gov>



ETA Tool Use Case

Fault Isolation Report Detail

- Failure modes are grouped by their “detection signature” – the set of tests that detect the propagated effects
- Fault isolation information can be used to verify Caution & Warning or Launch Commit Criteria (LCC) strategies when detection must identify a specific set of failure modes.

Failure Mode Group #22

Detection Signature: 3 Tests

Sensor Identifier	Schematic Identifier	Sensor Description	Test
SEN0026	D4	Yaw LVDT Displacement Transducer 1	No Position Change
SEN0027	D5	Yaw LVDT Displacement Transducer 2	No Position Change
SEN0028	D6	Yaw LVDT Displacement Transducer 3	No Position Change

Failure Mode Group contains 2 Failure Mode(s)

System	Component	Failure Mode	FMEA Identifier	Criticality
Vector Control System	Power Valve	Stuck In NULL Position	MS-SS-ACT-02-002	1
Vector Control System	Yaw Actuator	Actuator Locked In Place	MS-SS-ACT-03-001	1



ETA Tool Use Case

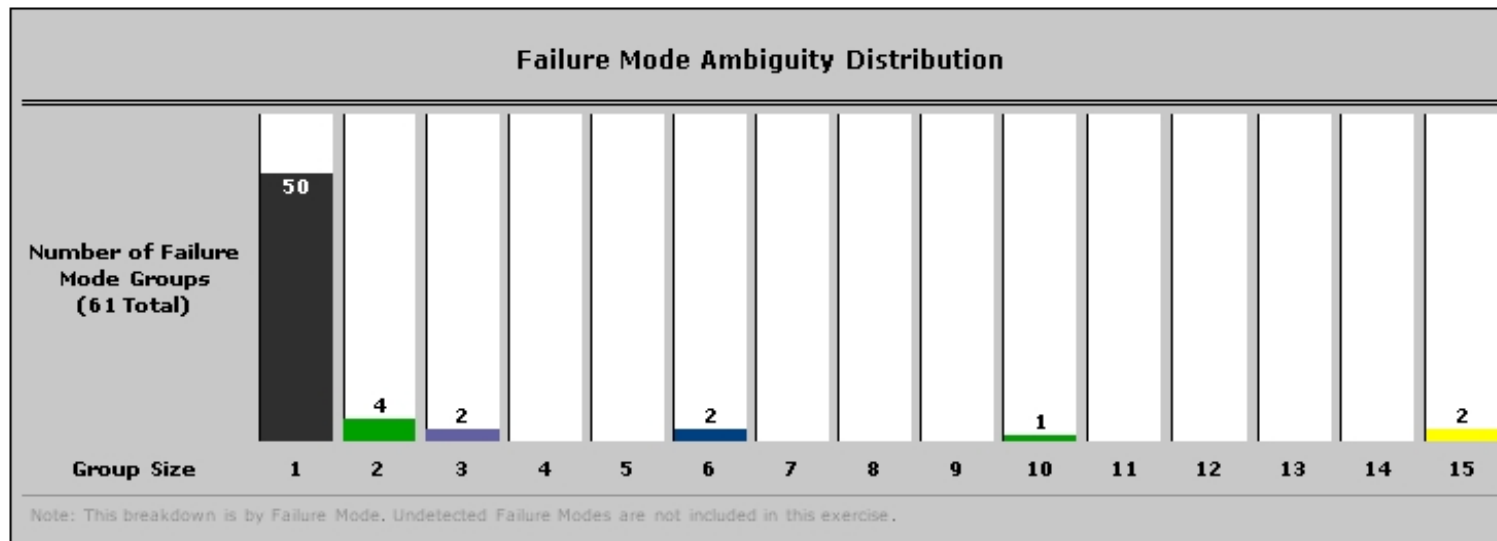
Fault Isolation Report Summary

Ambiguity Analysis

Number of Failure Mode Groups 61
 Number of Failure Modes..... 118
 Number of Isolated Groups..... 50
 Maximum Failure Mode Group Size..... 15
 Calculated Ambiguity Score..... 55

Ambiguity Distribution (Failure Mode Level)

Percentage of groups with 1 members 81.97% (50 of 61 groups)
 Percentage of groups with 2 members 6.56% (4 of 61 groups)
 Percentage of groups with 3 members 3.28% (2 of 61 groups)
 Percentage of groups with 6 members 3.28% (2 of 61 groups)
 Percentage of groups with 10 members 1.64% (1 of 61 groups)
 Percentage of groups with 15 members 3.28% (2 of 61 groups)





Concluding Remarks

- NASA Glenn developed software tools **available to U.S. Citizens** through the NASA Glenn Software Catalog/Repository (<http://sr.grc.nasa.gov>).
- Software Catalog includes software tools developed by the Controls and Dynamics Branch to support the assessment of System Health.
 - **ProDIMES** provides approach for fair, quantitative benchmark comparisons of aero engine gas path diagnostic methods.
 - **S4** provides software framework for optimally selecting sensors required to support the assessment of system health.
 - **ETA Tool** augments commercial-off-the-shelf software to provide testability analyses that support qualitative verification of system health requirements early in the design process.
- For more information contact *kjmelcher@nasa.gov*



References for ProDIMES

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2. Simon, D.L., "Propulsion Diagnostic Method Evaluation Strategy (ProDIMES) User's Guide," NASA TM-2010-215840, January 2010.
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2. Santi, L.M., Sowers, T.S., Aguilar, R.B., "Optimal Sensor Selection for Health Monitoring Systems," NASA TM-2005-213955, AIAA-2005-4485, June 2005.
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3. Maul, W.A., Fulton, C.E., “Extended Testability Analysis Tool User Guide,” NASA CR-2011-217240, November 2011.